

## Advantages of Muons

- Advantages of leptons over hadrons
  - ◆ Energetic
  - ◆ Interaction simplicity
- Minimal synchrotron radiation at high energies
  - ◆ Can bend: not forced to linac like  $e^-$ 
    - ★ Reuse accelerating structures
    - ★ Multiple collisions with one beam
      - > Can use larger spot size
  - ◆ No beamstrahlung
    - ★ Won't limit particles per bunch
    - ★ Won't increase effective energy spread
  - ◆ No stochastic radiation equilibrium emittance
- Disadvantages
  - ◆ Finite lifetime
    - ★ Determines many design choices
    - ★ Choices lead to other problems
  - ◆ High energy: neutrino radiation
    - ★ Highly penetrating

## General Considerations

- Longitudinal emittance of bunch small
  - ◆ Acceleration in RF (wavelength)
  - ◆ Cost reduction if smaller
  - ◆ Energy acceptance of lattice
- Transverse emittance small
  - ◆ Transport through lattice
  - ◆ Cost reduction if smaller

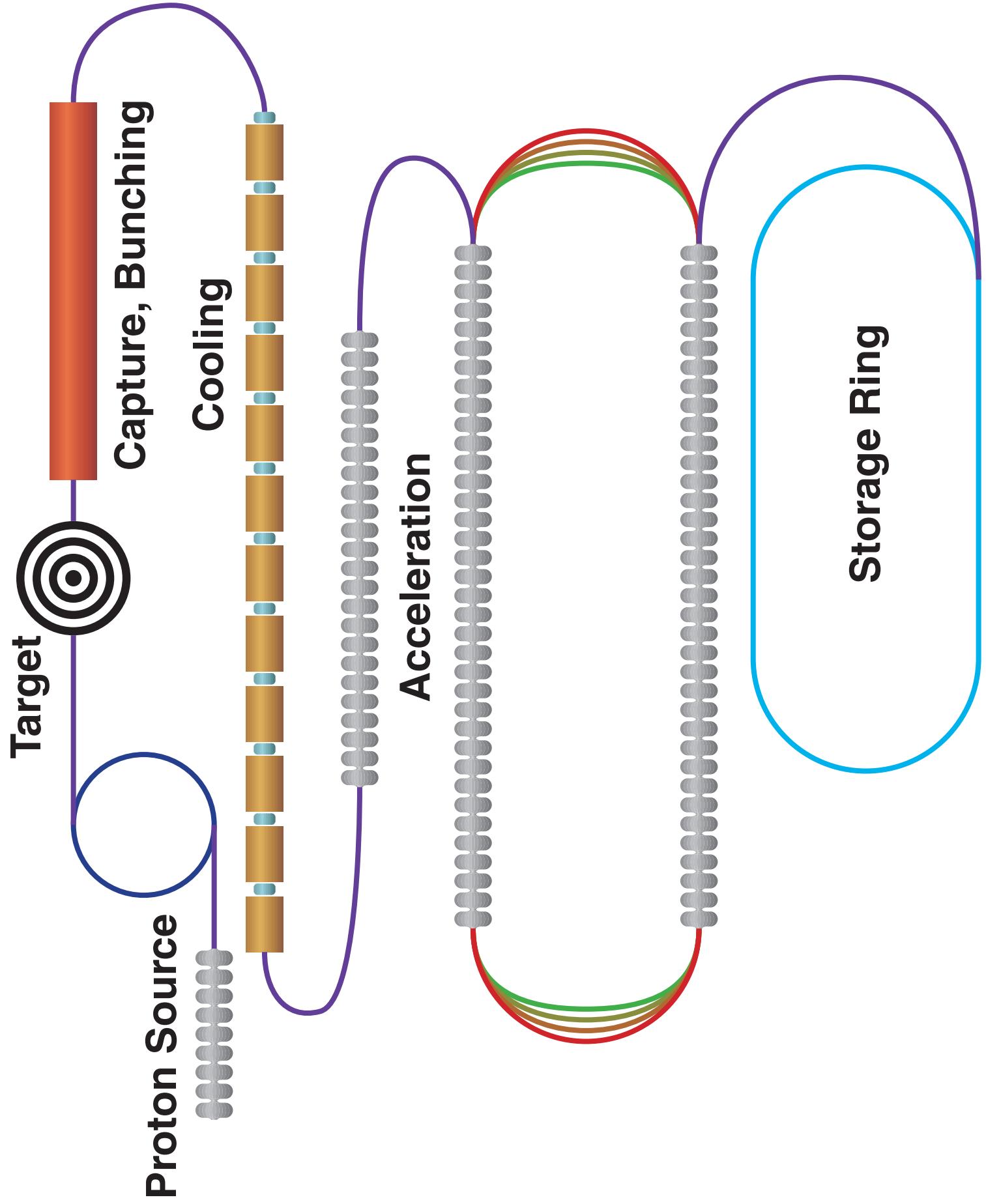
## Types of Machines

- Collider

- ◆ Small spot size
- ◆ Large charge per bunch
  - ★ Single bunch of each charge
- ◆ Small longitudinal emittance
  - ★ Short
  - ★ Small energy spread
- ◆ Higgs factory
  - ★ Extremely small energy spread (Higgs width)

- Neutrino factory

- ◆ Only total neutrinos to detector matters
  - ★ Multiple bunch scheme fine
- ◆ Single charge
- ◆ Physics gives modest limitations on beam size
  - ★ Transverse angular spread
- ◆ Studies
  - ★ Fermilab: 50 GeV, low yield
  - ★ BNL: 20 GeV, higher yield ( $2 \times 10^{20}$  muons/year)



## Muon Production

- Proton hits target, pions decay to muons
- Quantity
  - ◆ Roughly proportional to proton energy
  - ◆ Better for higher  $Z$ 
    - ★ Difference greater for higher energies
- Proton source
  - ◆ Measure in MW power on target: energy proportionality
  - ◆ 1-4 MW
  - ◆ Radiation at target
  - ◆ Upgrade existing machines (Fermilab, BNL)
- Target survival
  - ◆ Temperature rise
  - ◆ Shock stresses

## Muon Production, cont.

- Proposed solutions

- ◆ Carbon

- ★ Fermilab study
    - ★ Lower energy deposition in study, less chance of destruction
    - ★ Lower yield
    - ★ Lower  $\Delta T$

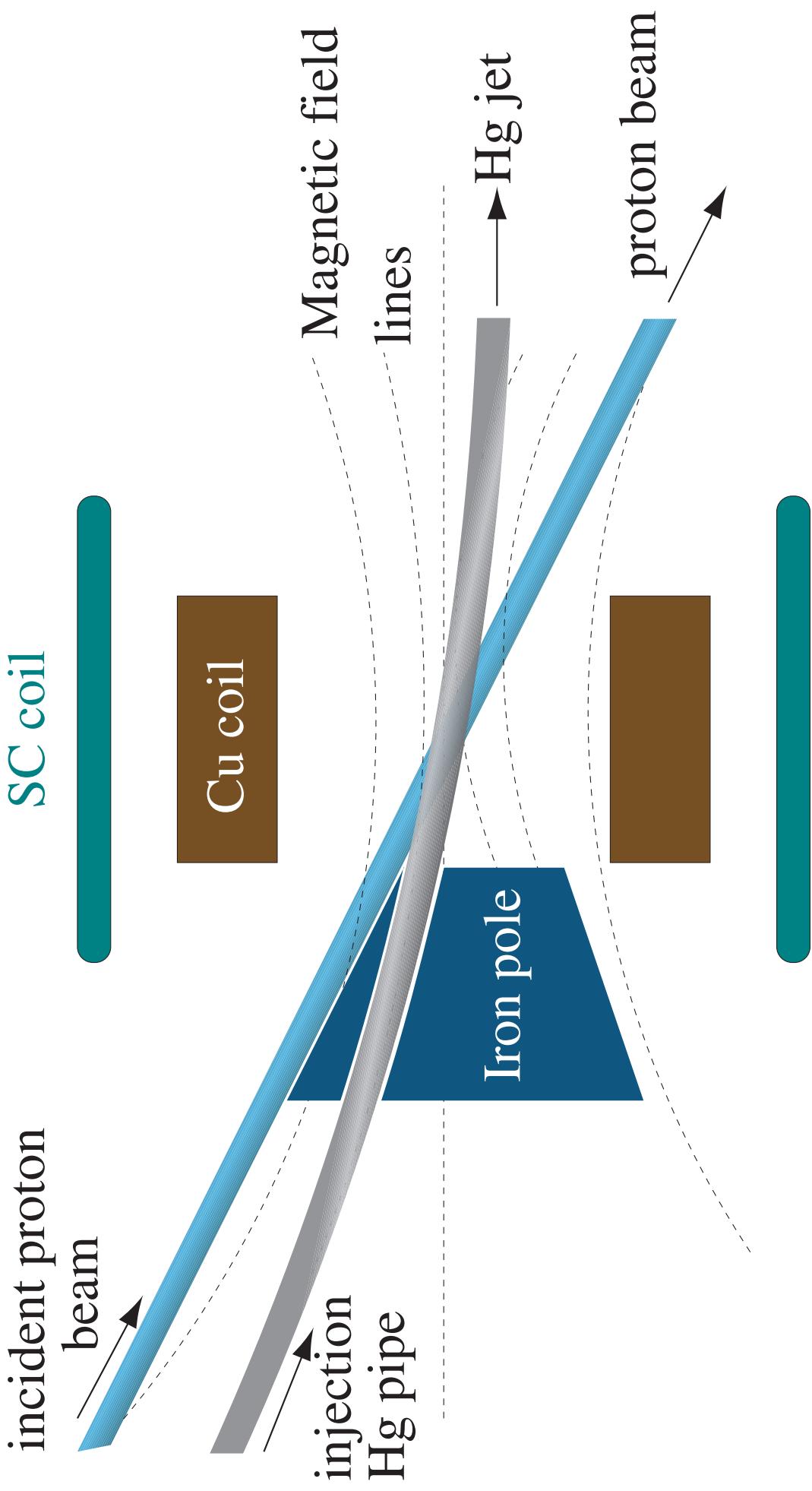
- ◆ Liquid Hg

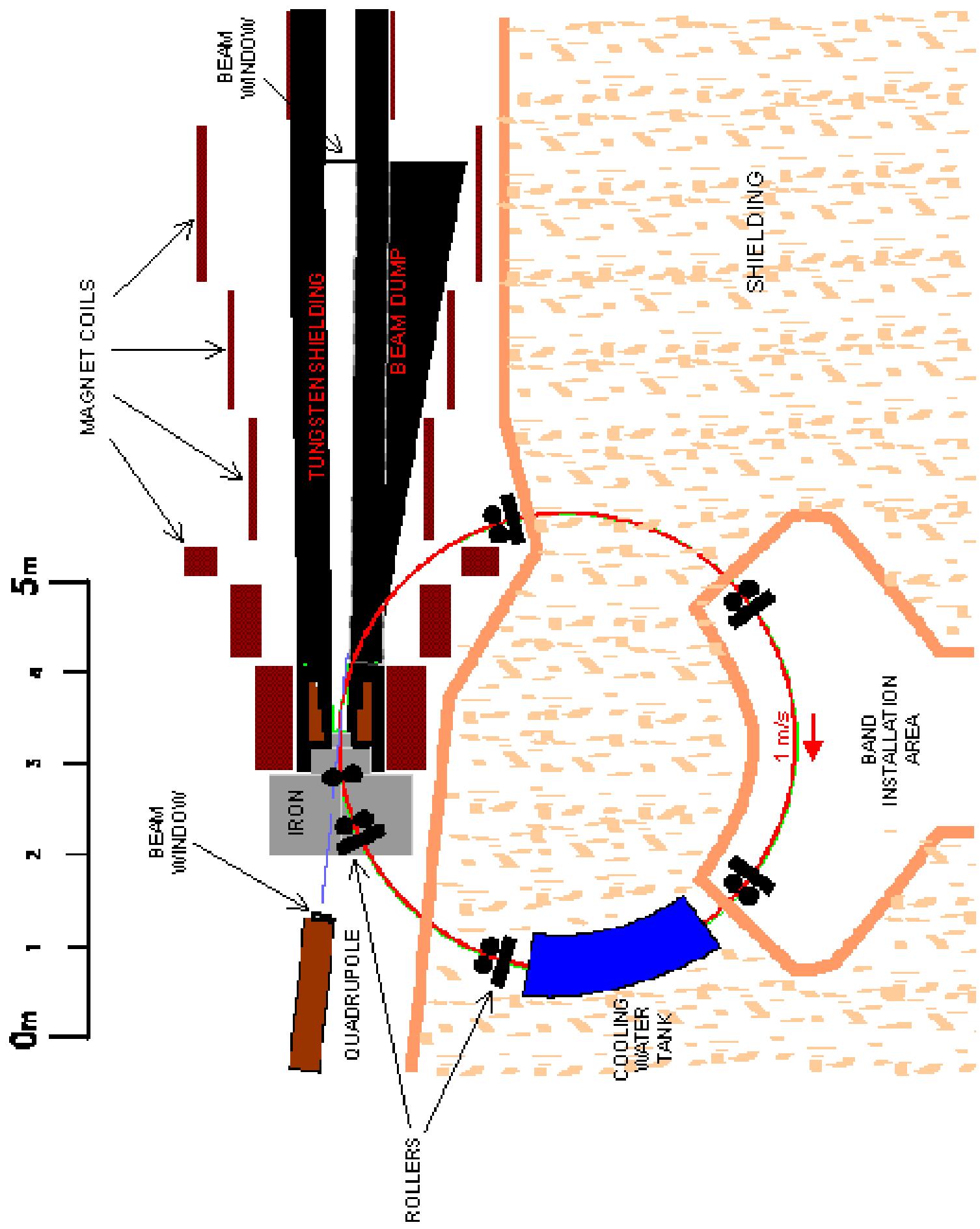
- ★ Avoid target destruction concerns
    - ★ Experiment planned

- ◆ Rotating Cu-Ni band

- ★ Spread beam out

- Radiation, handling





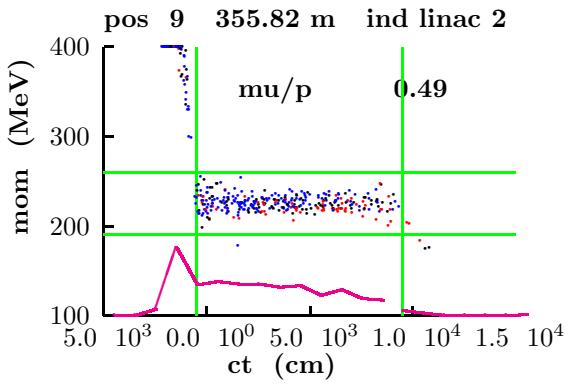
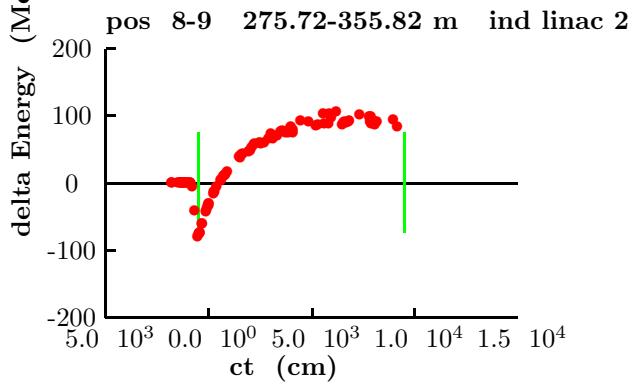
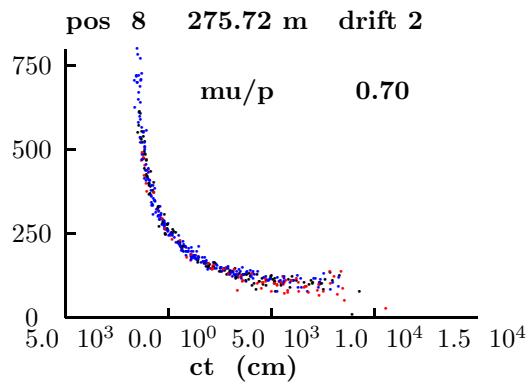
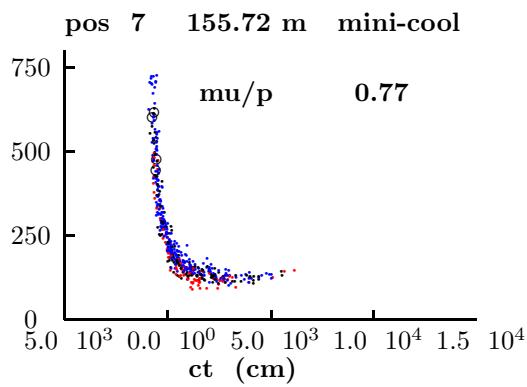
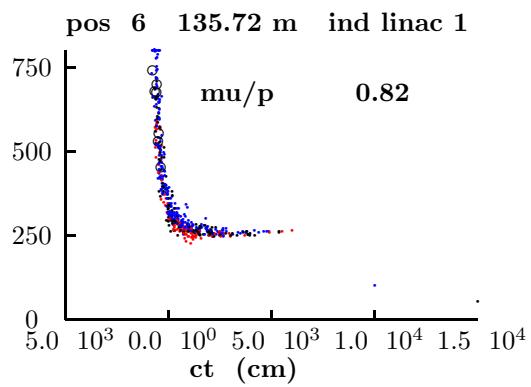
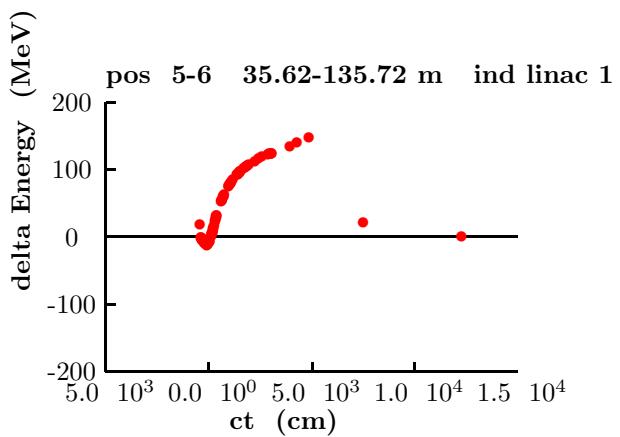
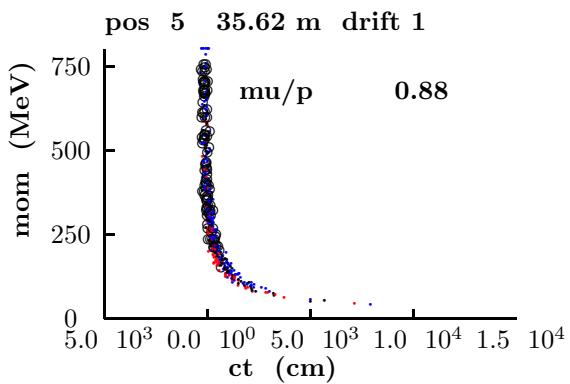
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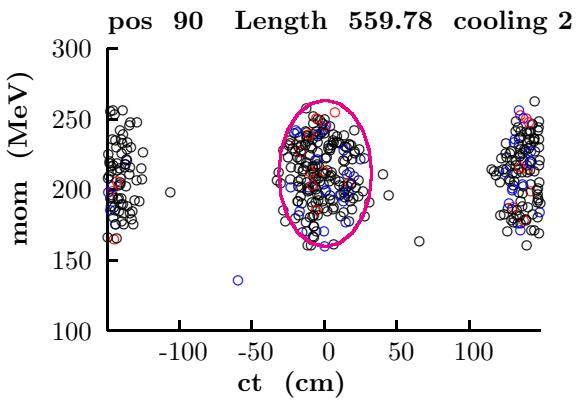
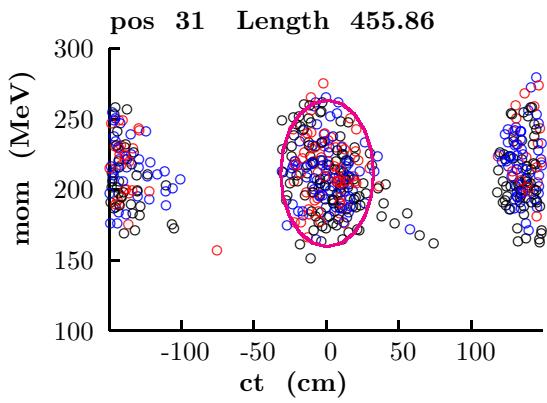
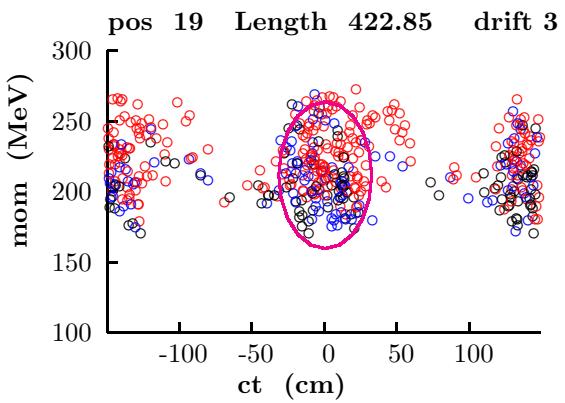
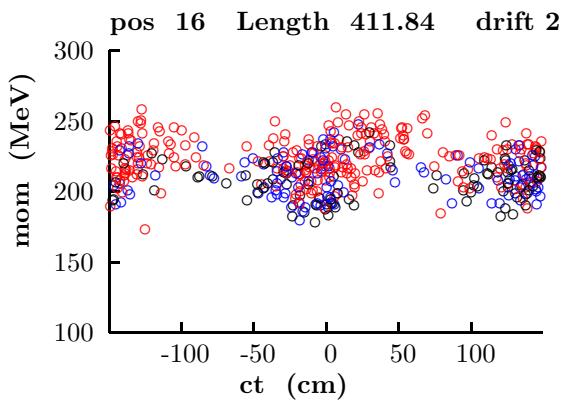
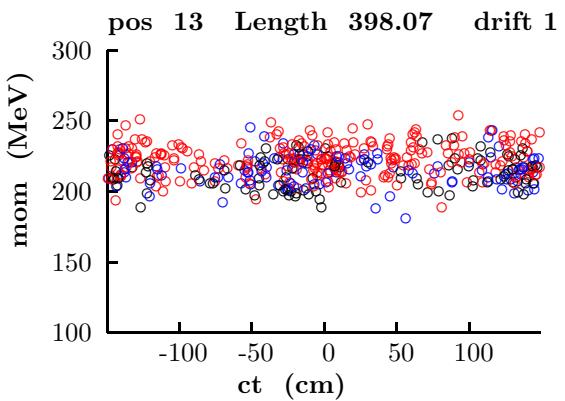
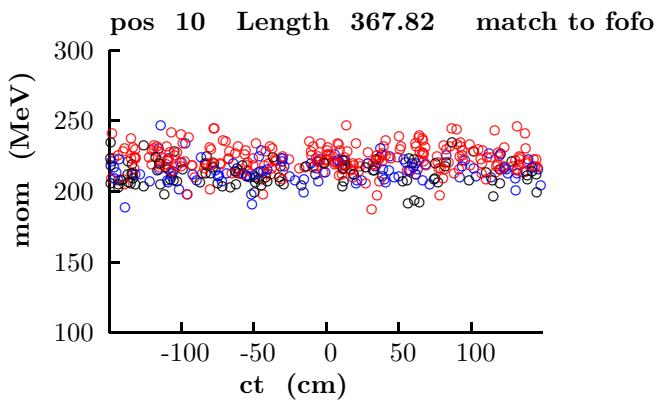
- Neutrino factory

- ◆ Create long bunch with small energy spread
  - ★ Drifts: nonlinear
  - ★ Induction linac (long pulse, RF won't work)
- ◆ Split into smaller bunches
  - ★ Needed small energy spread
  - ★ Lossy
    - > Fast: lose in-between particles
    - > Adiabatic: decay

- Muon collider

- ◆ Want everything in one bunch
- ◆ Have low-frequency RF close to target





# Cooling

- Principles

- ◆ Why:

- ★ Event rate proportional to beam density (collider)
- ★ Angular spread small (neutrino factory)
- ★ Losses in transporting large beam
- ★ Cost of transporting larger beam

- ◆ Ionization cooling

- ★ Other methods too slow

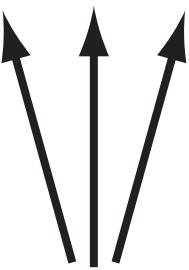
- ◆ Basic cooling

- ★ Lose energy in material
- ★ Momentum reduced in all directions
- ★ Restore longitudinal momentum only with RF
- ★ Result: transverse momentum reduced
- ★ Small effect longitudinally
  - > Derivative of  $dE/dx$  with energy
  - > Causes growth in our case

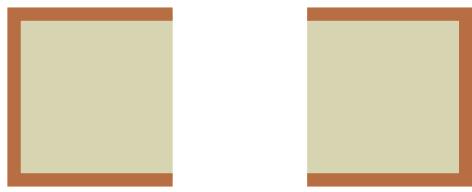
- ◆ Stochastic scattering

- ★ Given angular kicks
- ★ Keep RMS angle large in absorbers
  - > Relative effect small
  - > Difficult at higher energy

## Absorber



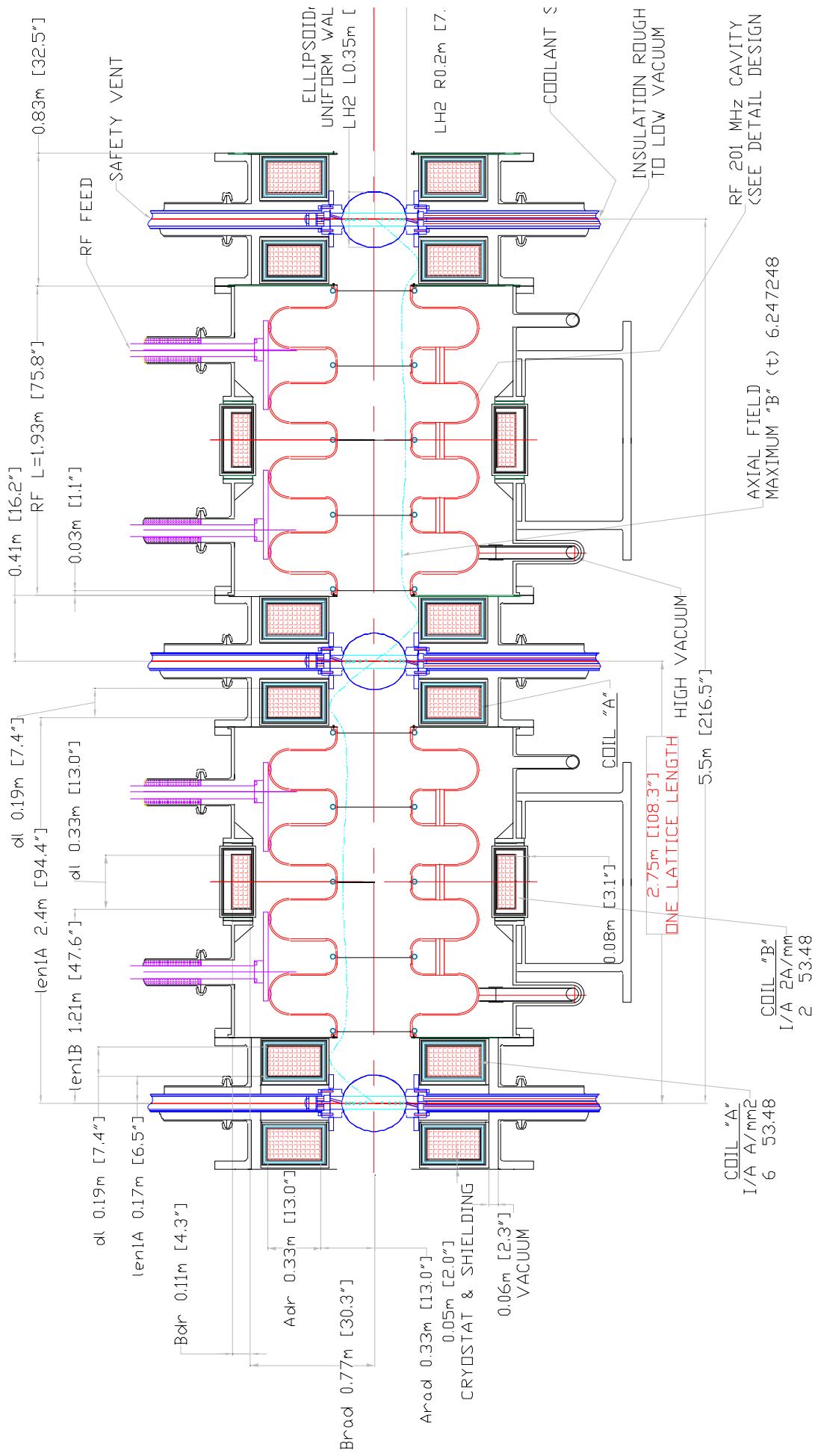
## RF Cavity



## Cooling, cont.

- Lattice

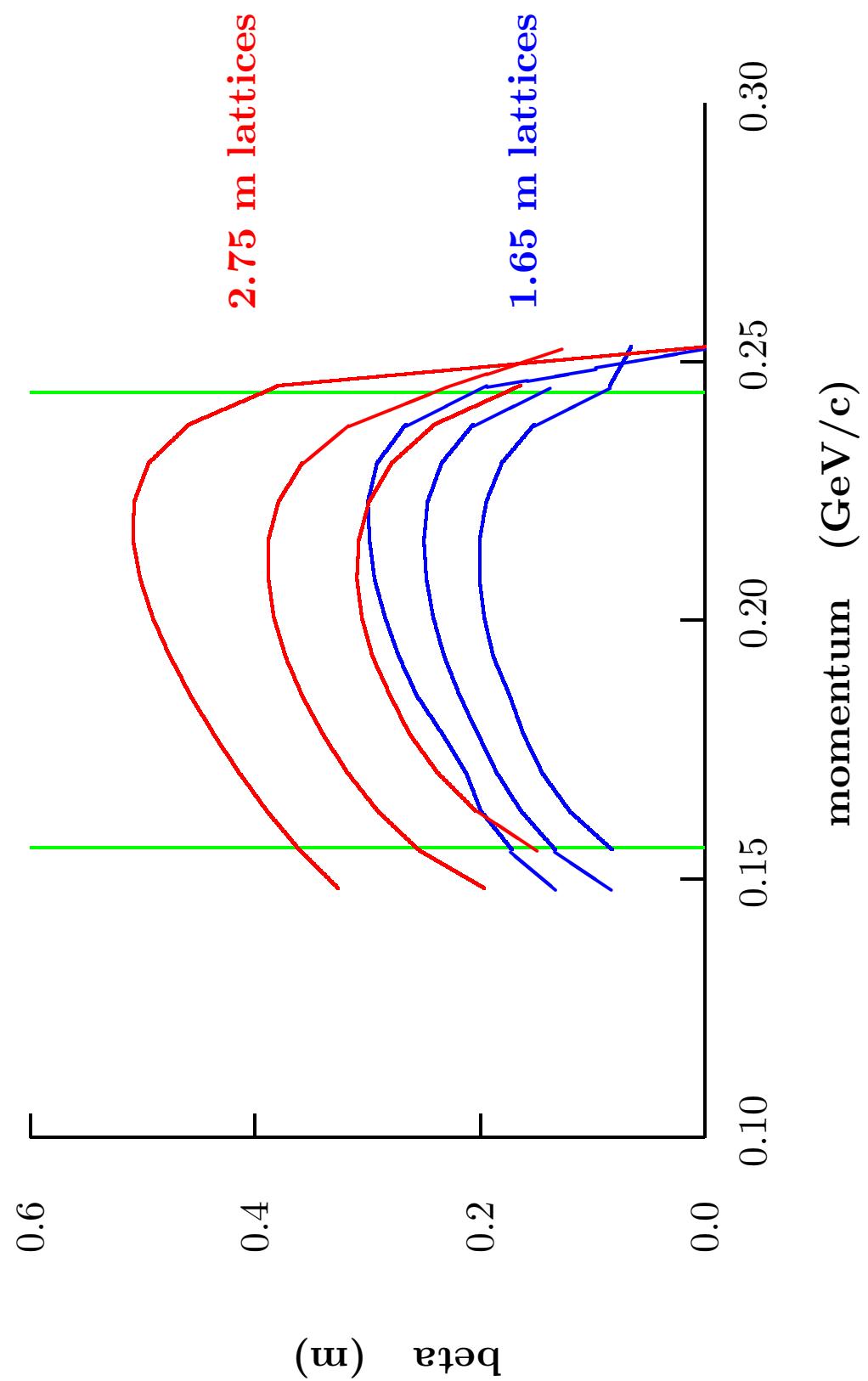
- ◆ Solenoid focusing
  - ★ Large beam
  - ★ Keep angle large
  - ★ High fields
  - ★ Requires NC RF: large power requirement
- ◆ Large energy spread
  - ★ Running between resonances
  - ★ Matching, linear modeling difficult
- ◆ Full longitudinal bucket
  - ★ Particles slowly spilling out longitudinally
- ◆ Figure of merit
  - ★ Particles within acceptance of downstream systems
  - ★ Increasing acceptance of downstream:  
significant cost increase
- ◆ Emittance profile

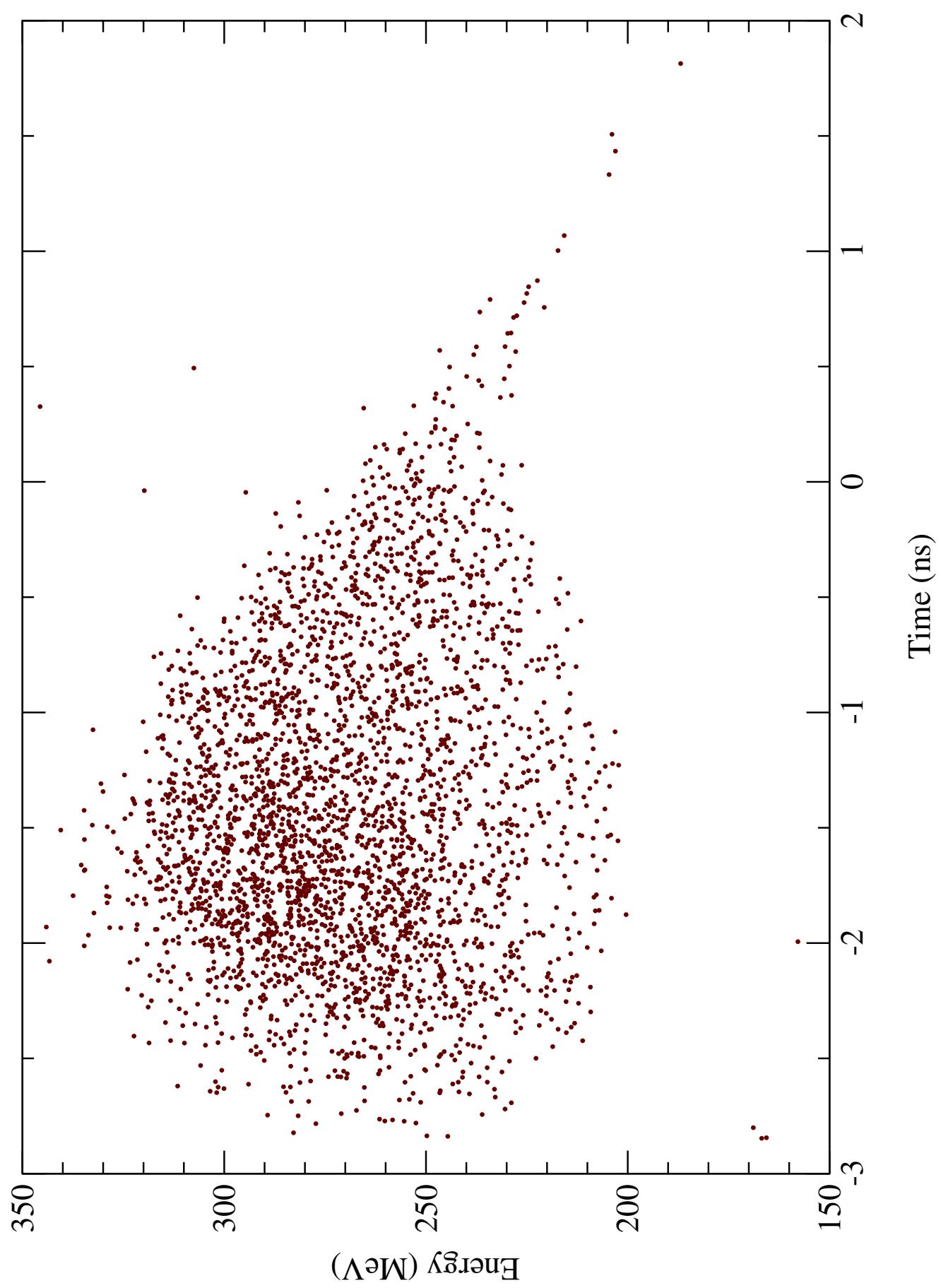


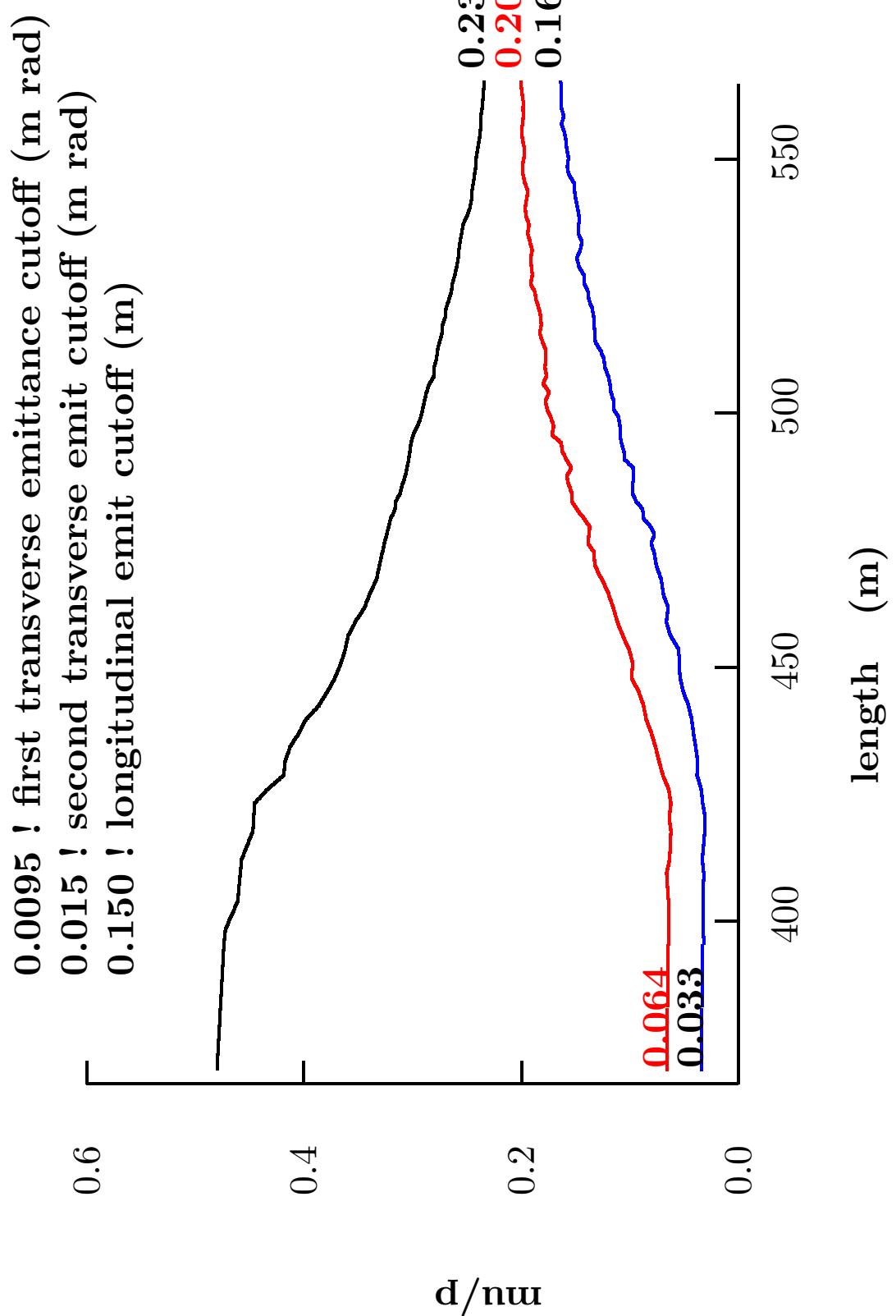
Superconducting Lattice  
at start of cooling  
(PRELIMINARY)

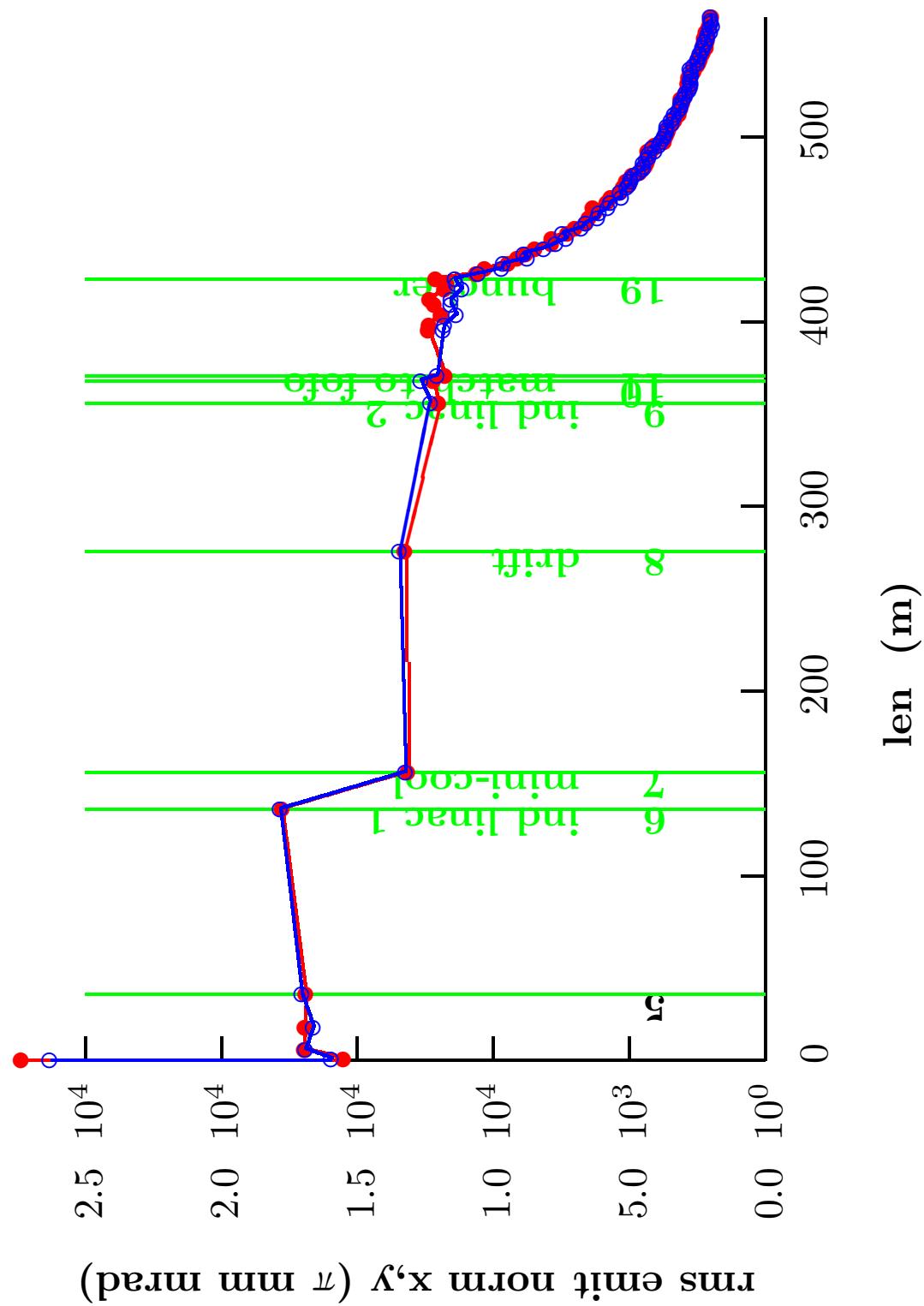
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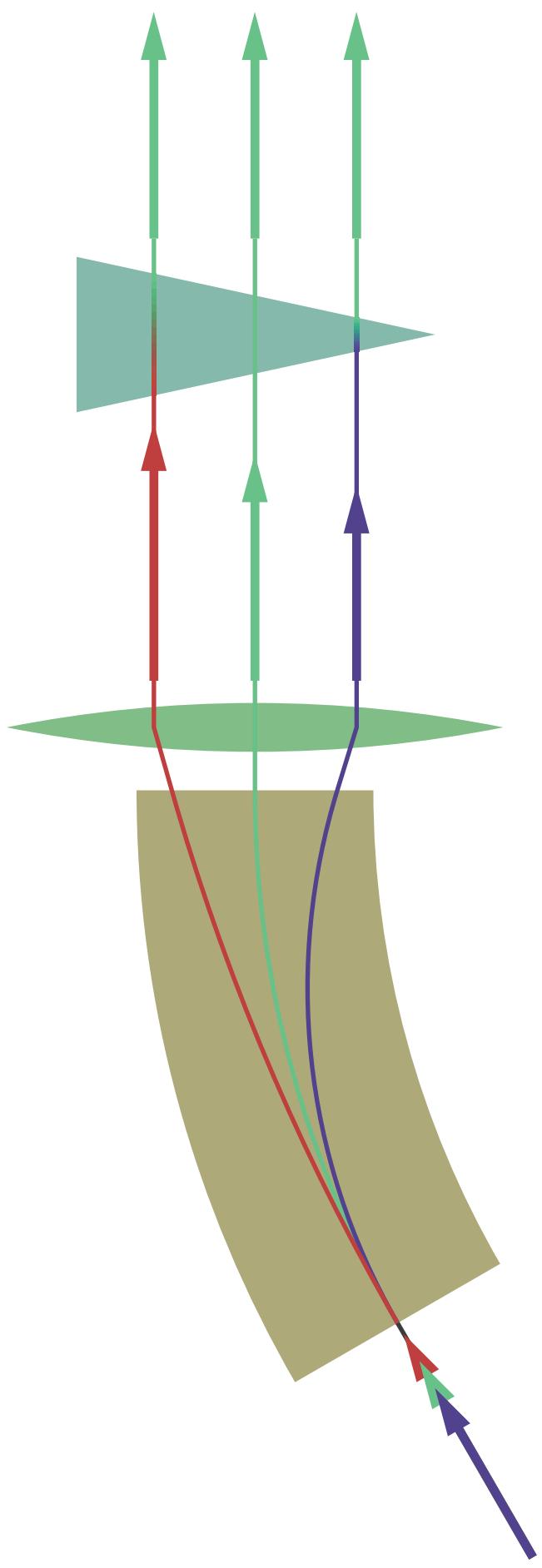
## Emittance Exchange

- Longitudinal Cooling

- ◆ Needed for collider (hourglass)
- ◆ Reduces cost of acceleration
- ◆ More cooling: not falling out of bucket

- Principle

- ◆ Create position dependence on energy (dispersion)
- ◆ Wedge of absorber:
  - ★ Energy loss depends on position
  - ★ Dispersion: energy loss depends on energy
  - ★ Reduce energy spread
- ◆ Cost: increased beam size
- ◆ Result: traded longitudinal beam size (emittance) for transverse
- ◆ Other methods
  - ★ Can completely exchange longitudinal phase space plane with one transverse
  - ★ Create rotated phase space at absorber: all three phase space planes have transverse momentum component



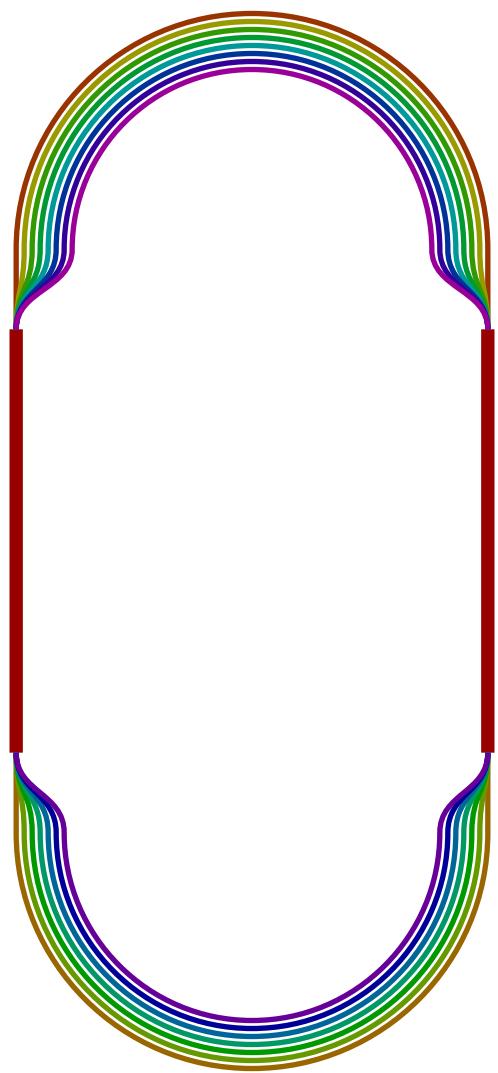
## Emittance Exchange, cont.

- Practical

- ◆ Have shown short sections with damping in all three phase space planes
- ◆ Longer sections more difficult
  - ★ Large beam size: linear approximation not so hot
  - ★ Difficult to match in 6-D phase space
  - ★ Bent solenoids

## Acceleration

- Major cost driver
- Must begin with linac
  - ◆ Large energy spread: difficult to bend
- Recirculating accelerator (CEBAF-style)
  - ◆ Principles
    - ★ Can bend muons, so reuse linac
    - ★ Need lots of RF per turn: decay
  - ◆ Large energy spread in arcs (around  $\pm 10\%$ )
    - ★ Emittance blowup
  - ◆ Keep peak power low
    - ★ SCRF
    - ★ Long fill times

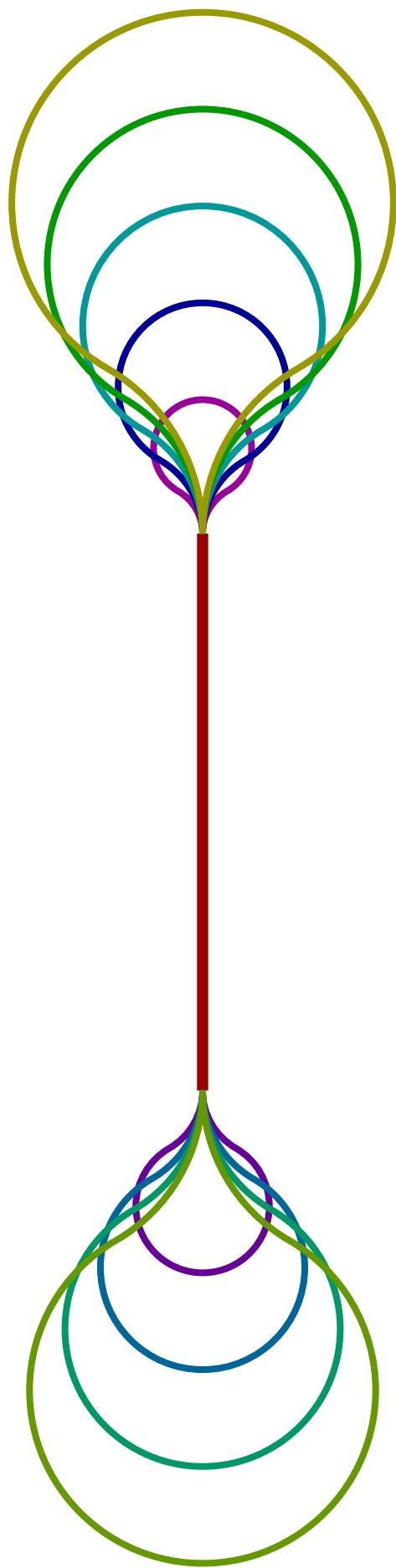


## Acceleration, cont.

- ◆ Large current: beam loading
  - ★ No time to replace extracted power
  - ★ Energy extracted by beam
    - > Just a couple percent: allows several passes
  - ★ Neutrino factory: bunch trains
    - > Front bunch extracts energy
    - > Rear bunch sees less voltage
    - > Different bunches have different energies after acceleration
  - ★ Collider: potential well distortion
  - ★ Need synchrotron oscillations
    - > Bunch loses too much energy
    - > Falls back, gains more energy
    - > Result: oscillations about correct energy
    - > More synchrotron oscillation, smaller amplitude oscillations
  - ★ Another option: use two close RF frequencies, beat wave
    - > On slope of beat wave, slope matches beam loading RF loss
    - > Waste linac: difference between gradient used and peak gradient

## Acceleration, cont.

- ◆ Geometry choices
  - ★ Racetrack: traditional design
  - ★ Dogbone
    - > Use same linac in both directions: cost savings
    - > Arcs get slightly longer
    - > Cost optimization
    - > Less complex switchyard
    - > Reverse bends
    - > Crossing lines
  - ★ Multi-sided
    - > Handle instabilities: create more synchrotron oscillations
    - > Overhead associated with switchyards greater
- ◆ FFAG arcs
  - ★ Re-use arcs, but arcs more expensive
  - ★ Avoid switchyards
  - ★ Energies can overlap:
    - > More turns
    - > More efficient RF use
    - > More decays
  - ★ Timing bunch to RF
    - > Isochronous arcs: no synchrotron oscillations, beam loading, sufficiently isochronous
    - > Shift RF phase: difficult

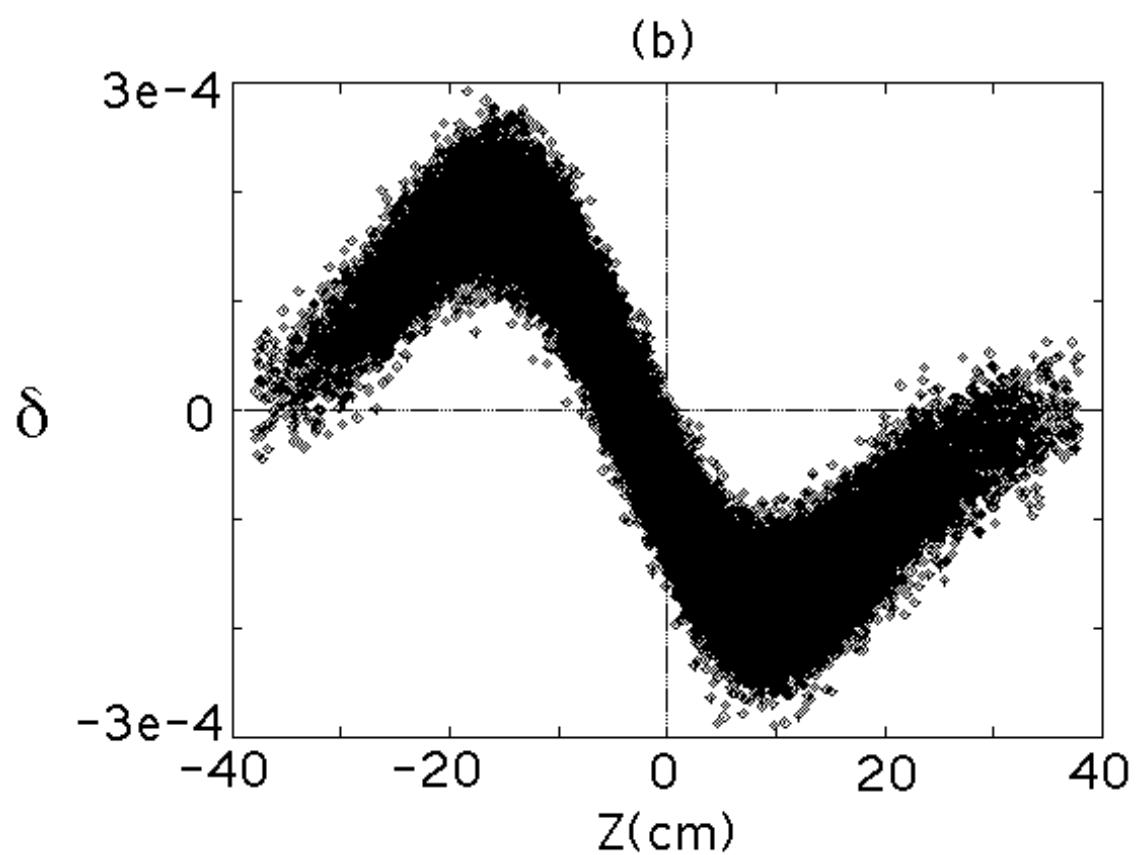
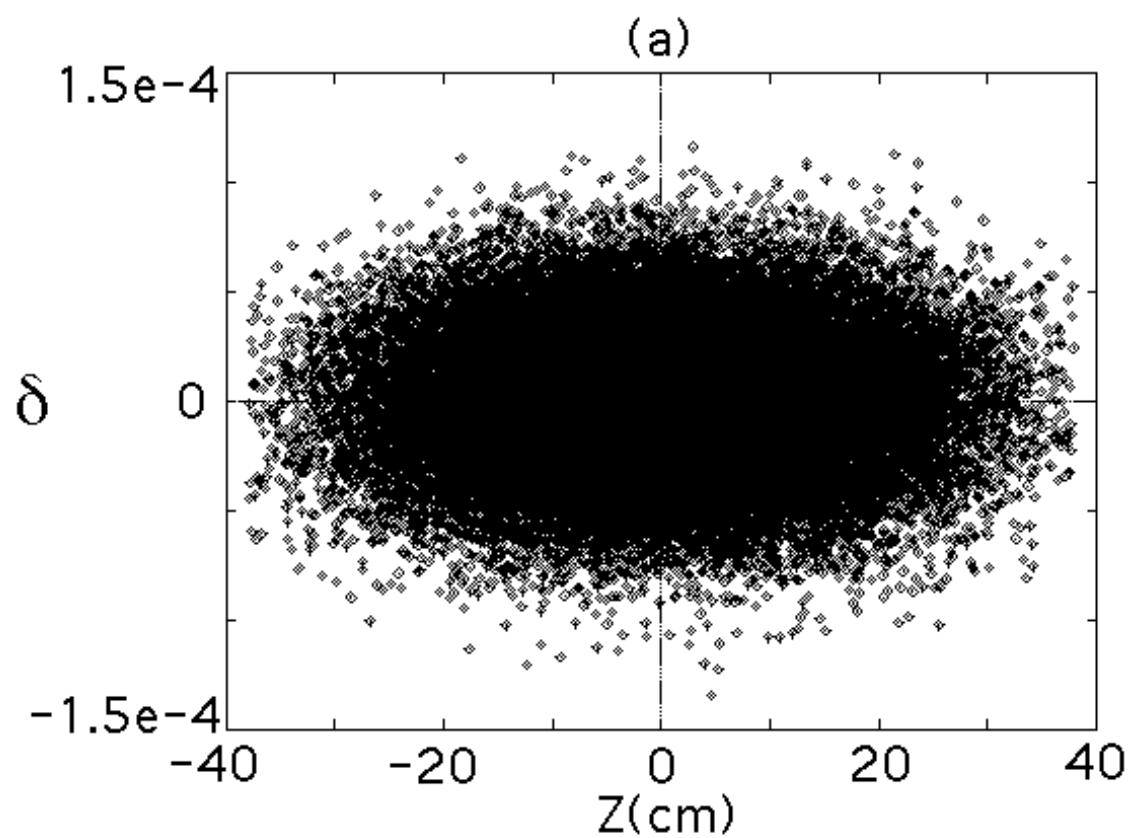


## Storage Ring

- Neutrino factory
- Long straights, pointed toward neutrino detector
  - ◆ Sloped
  - ◆ Deep underground: groundwater (limits BNL energy)
  - ◆ Longer straights, better efficiency
    - ★ Diminishing returns
  - ◆ Triangular, bowtie shape for two detectors
- Large energy spread (2%, better than the rest of system)
- Few hundred turns

## Collider: Higgs Factory

- Low energy (50+50)
- 1000 turns or so
- Extremely small energy spread ( $3 \times 10^{-5}$ )
- Collective effects
  - ◆ Large single bunch current
  - ◆ Infinite-time unstable
    - ★ Only 1000 turns: OK over that time frame
  - ◆ Wakefields increase energy spread
    - ★ RF cavities to correct
- Design being studied (Cline & Hanson)



## Collider: High Energy

- Neutrino radiation at high energies
- Being studied (Caldwell & King)

**TABLE 1.** Straw-man muon collider parameters. See overview write-up for details.

center of mass energy, E <sub>CoM</sub> description	0.1 to 3 TeV MCC status report	400 GeV top threshold	4 TeV frontier	30 TeV many-TeV
<b>collider physics parameters:</b>				
luminosity, $\mathcal{L}$ [cm <sup>-2</sup> .s <sup>-1</sup> ] $\int \mathcal{L} dt$ [fb <sup>-1</sup> /year]	(0.08 → 700) × 10 <sup>32</sup> 0.08→700 650→13 000	3.0 × 10 <sup>33</sup> 30 16 000	5.0 × 10 <sup>33</sup> 50 270	3.0 × 10 <sup>35</sup> 3000 290
No. of $\mu\mu \rightarrow ee$ events/det/year	2000→800 000	14 000	55 000	5 × 10 <sup>6</sup>
No. of (115 GeV) SM Higgs/year	0.02→1.1	1.4	1.0	0.14
CoM energy spread, $\sigma_E/E$ [10 <sup>-3</sup> ]				
<b>collider ring parameters:</b>				
circumference, C [km]	0.35→6.0	1.0	8.7	45
ave. bending B field [T]	3.0→5.2	4.2	4.8	7.0
<b>beam parameters:</b>				
( $\mu^-$ or) $\mu^+$ /bunch, $N_0$ [10 <sup>12</sup> ]	2.0→4.0	4.0	3.5	2.3
( $\mu^-$ or) $\mu^+$ bunch rep. rate, $f_b$ [Hz]	15→30	15	1.0	7.5
6-dim. norm. emit., $\epsilon_{6N}$ [10 <sup>-12</sup> m <sup>3</sup> ] $\epsilon_{6N}$ [10 <sup>-4</sup> m <sup>3</sup> .MeV/c <sup>3</sup> ]	170→170 2.0→2.0	170	170	100
P.S. density, $N_0/\epsilon_{6N}$ [10 <sup>22</sup> m <sup>-3</sup> ]	1.2→2.4	2.4	2.2	2.3
x,y emit. (unnorm.) [ $\pi.\mu\text{m.mrad}$ ]	3.5→620	41	2.4	0.19
x,y normalized emit. [ $\pi.\text{mm.mrad}$ ]	50→290	77	46	27
long. emittance [10 <sup>-3</sup> eV.s]	0.81→24	10	28	48
fract. mom. spread, $\delta$ [10 <sup>-3</sup> ]	0.030→1.6	2.0	1.4	0.20
relativistic $\gamma$ factor, $E_\mu/m_\mu$	473→14 200	1890	18 900	142 000
time to beam dump, $t_D$ [ $\gamma\tau_\mu$ ]	no dump	no dump	0.5	no dump
effective turns/bunch	450→780	620	450	1040
ave. current [mA]	17→30	24	0.63	12
beam power [MW]	1.0→29	3.8	2.2	83
synch. rad. critical E [MeV]	5 × 10 <sup>-7</sup> → 8 × 10 <sup>-4</sup>	1.1 × 10 <sup>-5</sup>	0.0013	0.11
synch. rad. E loss/turn	7 eV → 0.3 MeV	0.6 keV	700 keV	450 MeV
synch. rad. power	0.1 W → 10 kW	15 W	470 W	5.2 MW
beam + synch. power [MW]	1.0→29	3.8	2.2	88
decay power into beam pipe [kW/m]	1.0→2.1	2.1	0.06	0.8
<b>interaction point parameters:</b>				
rms spot size, $\sigma_{x,y}$ [\mu m]	3.3→290	18	2.7	1.0
rms bunch length, $\sigma_z$ [mm]	3.0→140	7.5	3.0	4.8
$\beta_{x,y}^*$ [mm]	3.0→140	7.5	3.0	4.8
rms ang. divergence, $\sigma_\theta$ [mrad]	1.1→2.1	2.3	0.90	0.20
beam-beam tune disruption, $\Delta\nu$	0.015→0.051	0.056	0.083	0.092
pinch enhancement factor, $H_B$	1.00→1.01	1.02	1.08	1.09
beamstrahlung frac. E loss/collision	negligible	negligible	6 × 10 <sup>-9</sup>	9 × 10 <sup>-8</sup>
<b>final focus lattice parameters:</b>				
max. poletip field of quads., $B_{5\sigma}$ [T]	6→12	10	12	15
max. full aper. of quad., $A_{\pm 5\sigma}$ [cm]	14→24	18	18	18
quad. gradient, $2B_{5\sigma}/A_{\pm 5\sigma}$ [T/m]	50→90	110	130	160
approx. $\beta_{\max}$ [km]	1.5→150	8	140	1800
ff demag., $M \equiv \sqrt{\beta_{\max}/\beta^*}$	220→7100	100	7000	19 000
chrom. quality factor, $Q \equiv M \cdot \delta$	0.007→11	0.003	10	4
<b>neutrino radiation parameters:</b>				
collider reference depth, D[m]	10→300	20	300	100
ave. rad. dose in plane [mSv/yr]	2 × 10 <sup>-5</sup> →0.02	7 × 10 <sup>-4</sup>	9 × 10 <sup>-4</sup>	6
str. sec. len. for 10x ave. rad. [m]	1.3→2.2	1.6	1.1	1.9
$\nu$ beam distance to surface [km]	11→62	16	62	36
$\nu$ beam radius at surface [m]	4.4→24	8.4	3.3	0.25